Coastal polynyas in the southern Weddell Sea: Variability of the surface energy budget

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[1] The surface energy budget of coastal polynyas in the southern Weddell Sea has been evaluated for the period 1992–1998 using a combination of satellite observations, meteorological data, and simple physical models. The study focuses on polynyas that habitually form off the Ronne Ice Shelf. The coastal polynya areal data are derived from an advanced multichannel polynya detection algorithm applied to passive microwave brightness temperatures. The surface sensible and latent heat fluxes are calculated via a fetch-dependent model of the convective-thermal internal boundary layer. The radiative fluxes are calculated using well-established empirical formulae and an innovative cloud model. Standard meteorological variables that are required for the flux calculations are taken from automatic weather stations and from the National Centers for Environmental Production/National Center for Atmospheric Research reanalyses. The 7 year surface energy budget shows an overall oceanic warming due to the presence of coastal polynyas. For most of the period the summertime oceanic warming, due to the absorption of shortwave radiation, is approximately in balance with the wintertime oceanic cooling. However, the anomalously large summertime polynya of 1997–1998 allowed a large oceanic warming of the region. Wintertime freezing seasons are characterized by episodes of high heat fluxes interspersed with more quiescent periods and controlled by coastal polynya dynamics. The high heat fluxes are primarily due to the sensible heat flux component, with smaller complementary latent and radiative flux components. The average freezing season area-integrated energy exchange is 3.48×10^{19} J, with contributions of 63, 22, and 15% from the sensible, latent, and radiative components, respectively. The average melting season area-integrated energy exchange is -5.31×10^{19} J, almost entirely due to the radiative component. There is considerable interannual variability in the surface energy budget. The standard deviation of the energy exchange during the freezing (melting) season is 28% (95%) of the mean. During the freezing season, positive surface heat fluxes are equated with ice production rates. The average annual coastal polynya ice production is 1.11×10^{11} m^3 (or 24 m per unit area), with a range from 0.71×10^{11} (in 1994) to 1.55×10^{11} m^3 (in 1995). This can be compared to the estimated total ice production for the entire Weddell Sea: on average the coastal polynya ice production makes up 6.08% of the total, with a range from 3.65 (in 1994) to 9.11% (in 1995). *INDEX TERMS:* 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4504 Oceanography: Physical: Air/sea interactions (0312); *KEYWORDS:* polynyas, sea ice, Weddell Sea, surface energy budget, surface fluxes, high-salinity shelf water

1. Introduction

[2] Coastal polynyas are regions of open water, or thin ice, formed by offshore winds blowing the sea ice pack out to sea. Their fixed locations provide a focus for wintertime air-sea-ice interactions within the polar regions, as the exposure of belts of relatively warm water to the cold polar atmosphere allows the exchange of vast quantities of heat, cooling the surface ocean and warming the boundary layer of the atmosphere. If the ocean is at freezing point, the cooling results directly in ice production; hence there is a release of latent heat and a rejection of salt as ice is formed. The rejected salt-enriched brine acts as a positive density forcing [e.g., *Curry and Webster*, 1999]. The atmospheric warming leads to changes in boundary layer dynamics, for example, the generation of convective plumes and, in general, an increase in boundary layer winds due to downward momentum transport [e.g., *Dare and Atkinson*, 1999]. The latent heat of fusion released as ice forms within wind-generated polynyas means they are often referred to as "latent heat" polynyas [e.g., *Smith et al.*, 1990].

[3] The impact of coastal polynyas on the ocean is important for several reasons. The fixed location, tied to the coastline and in regions prone to strong wind forcing, means the density forcing of the ocean is also spatially fixed. Indeed, as the air-sea exchange within a polynya is 1 or 2 orders of magnitude greater than through the surrounding sea ice, the local ocean forcing is likely to be dominated by the coastal polynya contribution. In this study we focus

on the coastal polynyas that habitually form off the Ronne Ice Shelf, in the southern Weddell Sea (Figure 1). This is an important region oceanographically as it is in the Weddell Sea that the major portion of Antarctic Bottom Water (the most extensive water mass in the world ocean) is thought to be generated through a number of pathways [e.g., *Foldvik and Gammelsrød*, 1988]. Most of the pathways have as a starting point High Salinity Shelf Water, a dense water mass formed by salinization of Circumpolar Deep Water over the continental shelf. The salinization is caused by the production of sea ice, and as coastal polynyas tend to be located over the continental shelves, they are thought to be the primary production sites of High Salinity Shelf Water.

Figure 1. A map of the southern Weddell Sea region. The study region is marked by the inner rectangle.

6. Conclusions

[51] The surface energy budget of coastal polynyas in the southern Weddell Sea has been investigated through the combination of satellite observations, meteorological data, and simple physical models. The surface energy budget time series are illustrated through Figures 10–15 and Tables 4–7. For coastal polynyas in the freezing season, positive sensible heat fluxes dominate the surface energy budget, with latent and radiative heat fluxes generally augmenting the oceanic cooling. The turbulent heat fluxes are characterized by episodes of high heat fluxes, interspersed with more quiescent periods. Coastal polynya dynamics set the timescales for these changes: strong offshore winds blow open the polynyas, which then refreeze at rates determined by the atmospheric and oceanic conditions. The total wintertime energy exchange is related to the cumulative coastal polynya area (indeed, the turbulent heat fluxes are strongly related); however, the varying atmospheric boundary layer is also important in modifying the fluxes. On average, the total energy exchange is 3.48×10^{19} J, with contributions of 63, 22, and 15% from the sensible, latent, and radiative terms, respectively. The wintertime energy exchange is not related to the length of the freezing season. For coastal polynyas in the melting season the area-integrated fluxes are dominated by the absorption of shortwave radiation. Over the 7 year period from 1992 to 1998 the ocean warms more than it cools through the presence of coastal polynyas. In particular, the anomalous summertime open water area of 1997–1998 allowed an enormous area-integrated warming of the ocean.

[52] During the freezing season, positive surface heat fluxes have been equated with ice production rates. The mean average coastal polynya ice production per unit area is 24.0 m, with a range from 15.6 (in 1998) to 31.7 m (in 1992). In terms of total annual coastal polynya ice production the mean is 1.11×10^{11} m^3 with a range from 0.71×10^{11} (in 1994) to 1.55×10^{11} m^3 (in 1995). The interannual variability is large: the standard deviation is 28% of the annual mean. Ice production has roughly a normal distribution over the freezing season, with strong modifications due to the episodic nature of the time series, for example, coastal polynya opening episodes may span a couple of months. These ice production calculations are compared to estimates of the ice production in the entire Weddell Sea from passive microwave data and an assumed average ice thickness of 0.5 m. The mean coastal polynya ice production is 6.08% of the entire Weddell Sea ice production, although this ratio varies from 3.65 (in 1994) to 9.11% (in 1995). The total annual Weddell Sea ice production does not vary that much: the standard deviation is only 5% of the mean. Hence variability in the ratio is determined primarily by changes in the coastal polynya ice production.

[53] An estimate of the accuracy of these results can be made through a comparison of the 1998 AWS and NCEP surface energy budgets. In the mean the components match remarkably well (to within 10 W m^{-2}). The correlation coefficients are over 0.75, and the linear regression slopes are over 0.8. The differences in mean monthly ice production are 8% over the whole year but only 2% if the anomalous months of February and March 1998 are ignored. This suggests that the use of the NCEP model data is well founded. For example, we would expect the time series to be accurate to within ~5% in terms of annual ice production. In addition to this however, there will be errors associated with (1) the determination of the sea ice cover, (2) the representativeness of the meteorological data, (3) the neglected physical processes in the CIBL model, and (4) the use of simple formulae for the radiative terms. We would estimate absolute errors associated with the above to be of the order 20%, in terms of the annual ice production, for example, but much less than that, of order 10%, when examining the interannual variability within the climatology. We are therefore confident that the interannual variability described here is genuine.

[54] A number of directions for future research have become apparent during this study. The transformation of this surface energy budget into an oceanic buoyancy forcing is one objective of future work. To do this will involve the assessment of a number of physical processes that affect both the heat flux and, in particular, the freshwater flux, for example, precipitation, blowing snow deposition, ice shelf melt, and changes inthe oceanographic conditions. The buoyancy forcing is a key ingredient for ongoing studies of sub–ice shelf oceanography and bottom water formation [*Nicholls and Makinson*, 1998; *Comsio and Gordon*, 1998], and so, a study along these lines is planned.